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Carbon and nutrient stocks in the litter layer of agroforestry systems in central Amazonia, Brazil

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Abstract

Both second-growth and agroforestry systems (AFs) have the potential for recovering thousands of abandoned pasturelands in Amazon. The AFs may do it faster and, at the same time, produce direct economic benefits for farmers. Improved nutrient recycling may be expected due to distinctive litter production in AFs, but lacks experimental data yet. The stocks of carbon and nutrients of the litter layer under different agroforestry systems (AFs) were investigated at an abandoned pasture site, 60 km north of Manaus. The experimental design consisted of three blocks, with five treatments: four different types of 5-year-old AFs and a secondary forest (CAP). Litter layer was sampled in the wet and dry seasons, sorted according to the predominant plant species and analysed for carbon and nutrient concentrations. The litter layer in the control plots was much larger than in the AFs, and thus, the carbon stocks in the litter layer of the control (wet = 489 g m^2; dry = 783 g m^2) were larger than in the AFs. However, due to a clearly higher concentration of nutrients in the litter from the AFs, some nutrient stocks were similar or even greater than in the control. The planted timber species and the green manures were important sources of K and Ca to the litter layer while the peach-palm was an important source of Mg. In general, the litter of AFs had lower C:nutrient ratios than the litter in the secondary forest control, indicating a faster nutrient recycling in the AFs.

Introduction

The *terra firme* rain forest, with high biomass and diversity of species, is the most representative ecosystem in terms of area coverage in the Amazon (Pires and Prance 1985). Most of these forests are located on nutrient-poor soils, thus depending upon a closed nutrient cycling to survive and grow (Herrera et al. 1978). In this kind of cycling, the organic matter produced by the forest itself represents a component of vital importance for the majority of the functional processes taking place in the soil. The plant litter provides the largest contribution to the formation of the humic layers in the soil, and litter decomposition by soil organisms releases mineral nutrients for the plants (Herrera et al. 1978; Luizão and Schubart 1987).

The conversion of the tropical forests to other land uses generally ruptures ecosystem function. Up to 1997, in the Brazilian Amazon, 53 million

hectares were deforested, of which approximately 95% were converted into pastures, from which half or more are today considered degraded (Fearnside and Barbosa 1998); most of these areas are already abandoned. Thus, large extensions of abandoned lands could be made productive again, with the simultaneous objective of reducing the ecological impacts of new deforestation and to increase the productivity and economic profitability of the deforested land in a sustainable way (Vieira et al. 1993). The management of the secondary vegetation and tree-based systems can contribute significantly to recover soil productivity and the biodiversity of deforested and degraded areas (Vieira et al. 1993). Plantations of legume cover and trees that stimulate production of litter, roots and exudates, can recover the physical and biological functioning of the soil (Grimaldi et al. 1993). Soil organic matter and biota are of upmost importance for maintaining soil structure and fertility (Grimaldi et al. 1993), and the use of agroforestry systems could contribute to this objective (Szott et al. 1991).

The agroforestry systems (AFs) are defined as 'a series of practices of land uses where trees are managed with agricultural crops (agrosilvicultural system) or with pastures (agrosilvopastoral system)'. Agroforestry systems are increasingly being used to rehabilitate the productive capacity of degraded areas and thereby improve their social and agroecosystem services (Szott et al. 1991; Fearnside 1998). They should be considered as alternative land use systems for already deforested areas, instead of substitutes for primary forest (Fearnside 1998). The litter layer produced by the planted tree, grass, and cover crop species in the AFs is likely to have a significant positive impact on soil properties (Szott et al. 1991; Grimaldi et al. 1993).

The accumulation of the litter layer on the soil surface depends on many factors: the planted species, climate, management practices, and action of decomposing organisms (Luizão and Luizão 1991; Szott et al. 1991; Fernandes et al. 1997). In Brazilian Amazonia, litter production varies from 2 to 2.3 tons ha^{-1} in 6-year-old AFs (Gallardo-Ordinola 1999) and from 4.1 to 10.3 tons ha^{-1} in 10-year-old secondary forest (Mesquita et al. 1998; Gallardo-Ordinola 1999). The litter layer accumulation on soil surface vary from 4.47 to 5.25 tons ha^{-1} for young 5-year-old secondary forests (Mckerrow 1992; Yano 1994) and from 3.87 to 5.0 tons ha^{-1} for AFs in Rondonia (Quisen et al. 1996). However, no attempts were made to date in order to identify tree species which could contribute larger quantities and/or better quality litter to the system.

The objectives of this study were: (1) to determine the stocks of carbon and nutrients in the litter layer under different agroforestry systems growing on abandoned pastures, and (2) to identify plant species which can contribute more efficiently to the nutrient storage and cycling on the soil surface.

Material and methods

The study was conducted at the Experimental Station of CPAA/EMBRAPA (Center for Agroforestry Research in the Western Brazilian Amazon/Brazilian Agricultural Research Agency). The site is located 60 km north of Manaus (02°31′04″ S, 60°01′48″ W, 60 m a.s.l.), on the BR-174 (Manaus-Boa Vista) highway, km 53. The climate corresponds to the Ami type in the Köppen classification (Ribeiro and Adis 1984), with an annual mean rainfall of 2200 mm. During the present study, in 1997, climatic data were recorded at the Experimental Station of CEPLAC (5 km to southwest of the study area). Annual rainfall was 2167 mm, varying from 20.5 to 407 mm per month. There was a marked period of rains before the first collection (March-wet season), and a very dry period preceding the second sampling (August-dry season). The annual mean temperature was 26.2 °C, with minimum means of 22.4 °C and maximum of 32.8 °C; the relative air humidity varied between 81 and 90%, with an annual mean of 83.9%, characterizing the area as 'tropical rainy region'.

Litter layer samples

The litter layer samples were collected from three blocks with five randomly assigned treatments, in 0.3 ha (50 × 60 m) plots. Each block had four different agroforestry systems (AFs) and a control plot, where existing natural regeneration ('capoeira') was allowed to grow. The treatments were: Agrosilvicultural System 1 (AS1), based on three perennial fruit trees, two of which are palm

species, with 165 trees ha^{-1}; Agrosilvicultural System 2 (AS2), a multi-strata system, with three timber species and several perennial fruit trees with 91.5 trees ha^{-1}; Agrosilvopastoral System 1 (ASP1) and Agrosilvopastoral 2 (ASP2), with similar composition and arrangement (a legume cover crop, *Desmodium ovalifolium*, and the grass *Brachiara humidicola* or *B. brizantha*) with 55.8 trees ha^{-1} (Table 1); they differed only regarding the soil preparation: the ASP1 received an application of 2 tons ha^{-1} of lime $+20$ kg ha^{-1} of NPK, while the ASP2 had an application of just 20 kg P ha^{-1}; both treatments were applied only at the beginning of the experiment. All the AFs have live fences of *Gliricidia sepium*, which are pruned twice a year and prunings were spread as green manure within the plots; the plots were manually weeded periodically (typically three times a year, every year) and the weed biomass placed in the inter-rows. In the ASPs, in January, March (wet season) and August (dry season) of 1997 cattle was allowed to graze during 7 days each time; five animals were placed in the ASP1, and three in the ASP2, both by the first time in January 1997. All four AFs were 5-year-old, and each block had a 9-year-old plot of second growth (CAP) used as control. The CAP plots corresponded to abandoned pastures similar and adjacent to the ones abandoned during about 4 years and then used for installing the AFs; they were composed mainly by species of pioneer plants, among which *Vismia* spp. are dominant (E. Wandelli, personal communication 2003).

Litter layer sampling

Fifty samples of the litter layer from each treatment and each block were collected, with a 15×15 cm wooden frame. The litter sampling was repeated in March (wet season), and August (dry season) of 1997, after cattle grazing in the ASPs. A total of 750 samples was collected in each season.

The litter samples were air-dried for 3–4 days, then sorted into two main components: 'leaves' and 'woody material' (the component 'leaves' also included other fast-decomposing materials, such as flowers and fine plant residues), and oven-dried at 65–70 °C to constant weight, to obtain the mass of the litter layer. Then, the samples were grouped according to the predominant plant species of each treatment: in the AS1, composite samples of *Theobroma*, timber trees and palm trees were made; in the AS2, of *Theobroma*, timber trees and inter-row weeds; in the ASP1 and ASP2, *Desmodium*, *Brachiaria* and the timber trees (mahogany and *Schizolobium*); in the control plot (CAP), the litter layer was dominated by *Vismia* spp. The dried samples were ground in a Wiley mill before chemical analyses.

Chemical determination of nutrients in the litter layer

The litter samples were analyzed for total concentrations of carbon, nitrogen, phosphorus, potassium, calcium and magnesium. The carbon was determined in a Fisons Auto-analyzer, model NA 1500, with a gaseous phase; the nitrogen was determined by the Kjeldahl method (Anderson and Ingram 1993), after sulfuric digestion with sodium hiposulfite and salicilic acid, using black selenium as a catalyst; phosphorus, potassium, calcium and magnesium were determined in Atomic Absorption Spectrophotometer (AAS) after nitroperchloric digestion (Anderson and Ingram 1993). Two blanks and two control samples of known concentrations, obtained from the EMBRAPA and INPA Forest Nutrition reference laboratories, were included in each set of 40 samples. The readings were made in an AAS (Anderson and Ingram 1993), except phosphorus, determined in a Shimadzu UV-120-01 spectrophotometer.

Data analyses

The data were analyzed with Minitab for Windows. Due to heterogeneity of variance, the data were transformed to homogenize the variance, as follows: square root of litter layer biomass, square root of (x + 1) for the litter concentrations of P, K, Ca, Mg, and arcsin for the concentrations of total nitrogen and carbon. Analysis of variance (ANOVA) and Tukey tests were used to compare treatment and plant species means.

Table 1. Species planted in the agroforestry systems and the main species naturally occurring in the control in central Amazonia, Brazil.

Family	Scientific name	Common name	Treatments
Arecaceae	*Bactris gasipaes* Kunth	Pupunha	AS1
Rhamnaceae	*Colubrina glandulosa* Perkins	Capoeirão	AS1
Arecaceae	*Euterpe oleracea* Martius	Açai	AS1
Sterculiaceae	*Theobroma grandiflorum* (S) K. Schung	Cupuaçu	AS1 & AS2
Lecythidaceae	*Bertholletia excelsa* H.B.K	Castanha-do-Brasil	AS2
Caricaceae	*Carica papaya L.*	Mamão	AS2
Mirtaceae	*Eugenia stipitata* McVaugh	Araçá-boi	AS2
Rubiaceae	*Genipa americana* L.	Jenipapo	AS2
Malpighiaceae	*Malphigia emarginata* L.	Acerola	AS2
Passifloraceae	*Passiflora edulis* L.	Maracujá	AS2
Verbenaceae	*Tectona grandis* Nursery	Teca	AS2
Mimosaceae	*Inga edulis* Martius	Ingá	AS2 & ASPs
Mimosaceae	*Schizolobium amazonicum* Ducke	Paricá	AS2 & ASPs
Meliaceae	*Swietenia macrophylla* King	Mogno	AS2 & ASPs
Gramineae	*Brachiaria brizantha* (Hochst) Stapf	Braquiarão	ASP1
Gramineae	*Brachiaria humidicola* (Rendle) Schweinckt	Quicuio-da-Amazônia	ASP2
Fabaceae	*Desmodium ovalifolium* Wall	Desmódio	ASP1&ASP2
Rubiaceae	*Borreria verticillata* (L) G.F.W. Meyer	Vassoura-de-botão	CAP
Flacourtiaceae	*Laetia procera* (Poepping) Eichler	Erva-de-pássaro	CAP
Astercaceae	*Rolandra fruticosa* (L) Kuntze	Estrepe	CAP
Clusiaceae	*Vismia japurensis* Reich	Lacre vermelho	CAP
Clusiaceae	*Vismia cayennensis (Jacq.) Pers*	Lacre amarelo	CAP
Ceasalpinaceae	*Gliricidia sepium* (Jacq.) Walp	Gliricídia	Live fence

AS = Agrosilvicultural system; ASP = Agrosilvopastoral System; CAP = Second growth (control).

Results and discussion

Litter layer mass

In the wet season, the litter-layer mass (leaves + woody material) in all treatments was significantly lower than in the dry season (ANOVA, $F = 371$; $p < 0.001$), following a pattern already found in agroforestry systems in Rondônia (Quisen et al. 1996), and in primary forests in central Amazon (Luizão 1995). The increase of the litter layer in the dry season, in all the studied treatments and dominant plant species, can be attributed to a larger fall of plant debris at this time of the year, when decomposition is generally slow (Luizão and Schubart 1987). In the wet season, the litter-layer mass was significantly greater in the control (CAP) and ASP2 than in the other treatments ($F = 58.6$; $p < 0.001$) (Table 2); in the AFs, greater amounts were found on soil surface covered by litter of the planted timber trees, and of *Brachiaria* ($F = 31.2$; $p < 0.001$) than for the other species, except for *Desmodium*. In the dry season, the litter layer mass was lower in the AS1 (based on palm trees) and in the ASP1 (limed soil) than in the other treatments ($F = 36.5$; $p < 0.001$); within the AFs, larger amounts of litter ($F = 25.8$; $p < 0.001$) were found under palm trees and *Theobroma* than under the other species of plants, except for the inter-rows (Figure 1).

In both the wet and dry seasons, the litter mass in the 9-year-old secondary forest (CAP) was significantly higher than in most of the AFs (Table 2). This was likely a function of both greater litter production (Gallardo-Ordinola 1999) as well as slower decomposition rate of the litter layer in CAP when compared to the agroforestry systems, which were 4 years younger and, thus, had lower plant biomass. Slow decomposition rates for second growth leaf litter has been reported elsewhere in Central Amazonia (Yano 1994; Mesquita et al. 1998), opposed to fast decomposition rates for most AF species (Gallardo-Ordinola 1999).

The leaves of dominant *Vismia* species in the secondary forest vegetation are more resistant to decomposition than the leaves of most forest species (Yano 1994; Mesquita et al. 1998) and, possibly, more than the species planted in the AFs.

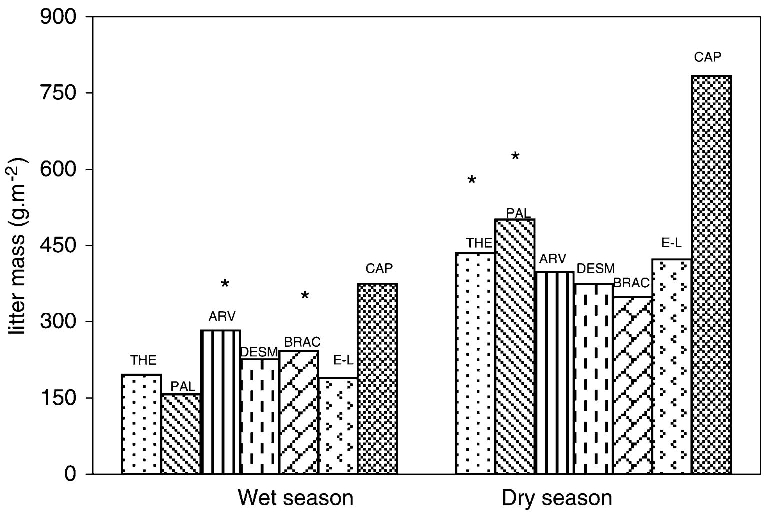

Figure 1. Litter-layer mass in the wet and dry seasons under agroforestry systems and secondary forest in central Amazonia, Brazil. Bars are the means of three blocks (n = 3), and asterisks indicate significant differences (p < 0.001) among the litter types, within the AFs (except CAP). AFs = agroforestry systems; THE = *Theobroma*; PAL = palms; ARV = timber trees; DES = *Desmodium*; BRA = *Brachiaria*; E–L = inter-rows and CAP = second growth.

Table 2. Litter-layer mass and percent composition (leaf and woody material), in the wet and dry seasons, in the agroforestry systems and in the control plot in central Amazonia, Brazil.

Treatments	Wet Season			Dry Season		
	Litter (g/m^2)	Leaf (%)	Woody (%)	Litter (g/m^2)	Leaf (%)	Woody (%)
AS1	154 ± 148a	64	36	448 ± 199a	79	21
AS2	266 ± 151a	67	33	557 ± 198b	77	23
ASP1	295 ± 158a	66	34	381 ± 153a	52	48
ASP2	327 ± 118b	62	38	487 ± 137b	52	48
CAP	489 ± 160 b	67	33	783 ± 213b	88	12

The values of the first column (litter mass) are means of three blocks ± standard errors.
Values followed by different letters in the columns indicate significant differences between treatments at the level of 0.1% (p < 0.001). Treatments as in Table 1.

The large litter-layer mass in the ASP2 system was most likely due to the presence of *Desmodium* and *Brachiaria*, both of which have high litter production (Corrêa and Corrêa 1996). On the other hand, cattle grazing on the ASP1 (limed soil) plots, caused a decrease of the litter layer in the dry season because the cattle has eaten a considerable proportion of the grass and *Desmodium*. This decrease was more evident in this ASP1 (more productive and heavily grazed) than in the ASP2 (less productive and less grazed).

The leaves are generally the main component of the fine litter layer both in volume and in dry weight, and their importance for nutrient cycling increases due to the fact that they decompose more quickly than woody components, releasing nutrients for the ecosystem (Herrera et al. 1978; Luizão and Schubart 1987). The amount of leaves in the litter layer (including eventual small amounts of reproductive materials and non-woody plant fragments) was significantly greater in the AS2 and in the control than in the other treatments (F = 84.3; p < 0.001) in the wet season (Table 2). In the dry season, greater amounts of leaves were found in the control and in the AS1 than in the other treatments (F = 90.8; p < 0.001) (Table 2). During the wet season, the amount of fine woody material (up to 2 cm diameter) in the litter layer was greater in AS1 and ASP2 than in the other treatments (F = 14.1;

Table 3. Concentrations of C, N, P, K, Ca and Mg of the leaf litter layer, in the wet and dry seasons, under the dominant plant species within the agroforestry systems and in the control plot in central Amazonia, Brazil.

Plant species	C (%)	N (%)	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})
Wet Season						
Theobroma	47.4 ± 0.4a	1.29 ± 0.4a	0.15 ± 0.1a	0.85 ± 0.6a	5.31 ± 0.3a	1.48 ± 0.3b
Palms	45.1 ± 0.0a	1.06 ± 1.2a	0.15 ± 0.0a	0.67 ± 0.1a	3.62 ± 0.7a	1.50 ± 0.2b
Timber spp.	45.3 ± 3.1a	1.52 ± 0.4b	0.16 ± 0.1b	0.79 ± 0.4a	7.24 ± 2.4b	1.38 ± 0.3a
Desmodium	49.1 ± 2.0b	1.55 ± 0.4b	0.12 ± 0.0a	0.61 ± 0.1a	6.03 ± 1.2b	1.22 ± 0.2a
Brachiaria	48.0 ± 8.6b	1.28 ± 0.2a	0.13 ± 0.0a	0.60 ± 0.1a	6.02 ± 1.6b	1.28 ± 0.3a
Inter-rows	43.5 ± 0.2a	1.11 ± 0.2a	0.17 ± 0.0b	1.04 ± 0.7a	3.57 ± 1.4a	1.31 ± 0.3a
Pioneer sp	51.4 ± 0.0b	1.11 ± 0.1a	0.10 ± 0.0a	0.57 ± 0.1a	5.43 ± 0.3a	1.24 ± 0.1a
Dry Season						
Theobroma	52.0 ± 0.1b	1.20 ± 0.3a	0.14 ± 0.1a	1.58 ± 0.4a	8.99 ± 2.2a	1.39 ± 0.3b
Palms	45.2 ± 0.0a	1.03 ± 0.1a	0.16 ± 0.0b	1.26 ± 0.4a	9.28 ± 3.2a	1.45 ± 0.3b
Timber spp.	52.4 ± 9.1b	1.63 ± 0.2b	0.15 ± 0.0b	1.94 ± 0.6b	11.1 ± 0.6a	1.31 ± 0.2a
Desmodium	49.4 ± 1.0a	1.62 ± 0.3b	0.12 ± 0.0a	1.18 ± 0.2a	9.0 ± 2.5a	1.29 ± 0.2a
Brachiaria	47.3 ± 0.1a	1.67 ± 0.2b	0.12 ± 0.0a	1.09 ± 0.2a	8.95 ± 2.8a	1.34 ± 0.3b
Inter-rows	59.6 ± 1.5b	1.15 ± 0.2a	0.17 ± 0.0b	1.63 ± 0.7b	10.7 ± 4.9a	1.09 ± 0.3a
Pioneer sp	50.6 ± 0.0a	1.08 ± 0.0a	0.09 ± 0.0a	1.55 ± 0.4a	6.45 ± 0.6a	0.99 ± 0.1a

The values represent the means of three blocks ± standard errors. Values followed by different letters in the columns indicate significant differences at the level of 0.1% ($p < 0.001$) among the treatments, within each season.

$p < 0.001$). In the dry season, greater amounts of woody material were found in ASP1 and ASP2 than in the other treatments ($F = 231$; $p < 0.001$) (Table 2). There was also a visible decrease of the proportion of woody material in the litter layer of the ASs 1 and 2 and in the control in the dry season; the opposite happened in the ASPs 1 and 2 (Table 2). The most probable cause for that in the ASPs was that *Desmodium* leaflets decompose very quickly (Gallardo-Ordinola 1999), leaving behind the fine twigs, which decompose slower, in the accumulated litter layer of the dry season. In this season, there was the additional effect of cattle grazing, removing almost all *Desmodium* and *Brachiaria* leaves and inducing a predominance of stems and twigs on the litter layer. The largest amount of woody material found in the ASP2, in both seasons, was due mainly to the fine branches and stems of *Desmodium*, with diameters < 2 cm but apparently with a slow decomposition rate.

Carbon and nutrient concentrations in the litter layer

Leaf-litter layer C concentrations showed relatively small differences among species dominating litter layer, even though some differences were significant (Table 3). In the wet season, C concentrations were higher in the litter layer dominated by pioneer species, *Desmodium* and *Brachiaria*, than under the other species ($F = 6.97$; $p < 0.001$); in the dry season, C concentrations were higher in the inter-rows, and under palm trees and *Theobroma* ($F = 11.7$; $p < 0.001$). Pioneer species generally showed high C and low nutrient concentrations (with the exceptions of K and Ca) (Table 3).

Leaf-litter layer dominated by timber trees generally presented higher concentrations of N, P, K and Ca than other dominant litters (Table 3); *Desmodium* dominated litter generally had higher concentrations of N and Ca; litter from the inter-rows had higher P and K concentrations; and, litter of *Theobroma* and palms had higher Mg (Table 3).

The N concentrations in leaf litter layer in SAFs were higher than in mature forests of Sarawak and Maracá (Proctor et al. 1983; Villela 1995), although lower than that found in a tropical lowland forest in Manaus (1.5%) by Luizão (1995) (Table 4). This value draws near to the concentrations of the ASPs in the present study, which uses as cover crop *Desmodium*, a nitrogen-fixing legume.

The *Theobroma* litter presented low P retention, with a concentration of just 0.15 g kg^{-1} (Table 3), much lower than the concentration generally found in the green leaves of the tree, 1.6 g kg^{-1} of total P (S. Alfaia, personal communication, 2003). This may indicate strong retranslocation of P

Table 4. Comparative values of litter-layer mass and concentrations of nutrients in secondary forests and agroforestry systems on terra firme in the tropics.

Ecosystem	Age (years)	Location	Season	Litter (tons ha^{-1})	Leaf (tons ha^{-1})	N (%)	P	K	Ca	Mg	References
							(g kg^{-1})				
Primary forest	–	Manaus/BR	W + D + W	6.5	2.78	1.5	0.28	1.08	1.62	1.14	Luizão (1995)
Primary forest	–	Maracá/BR	–	7.7	6.4	1.0	0.34	5.4	5.7	1.8	Villela (1995)
Primary forest	–	Jenaro Herrera/PE	W + D	15.8	12.0	1.62	0.83	4.52	3.23	1.48	Tapia-Coral (2004)
Forest *Dipterocarpus*	–	Sarawak	–	5.9	–	0.95	0.1	4.5	1.5	1.1	Proctor et al. (1983)
Secondary forest	5	Manaus/BR	D	5.25	–	1.09	0.3	2.9	6.4	1.3	Mckerrow (1992)
Secondary forest	5	Manaus/BR	W	4.47	–	–	–	–	–	–	Yano (1994)
Secondary forest	10	Manaus/BR	W + D	6.32	5.06	1.10	0.10	1.06	5.94	1.39	This study
Secondary forest	16	Jenaro Herrera/PE	W + D	13.5	10.2	1.44	0.48	1.36	4.98	1.36	Tapia-Coral (2004)
Desmodium ovalifolium	8	Manaus/BR	–	5.8	–	1.2	0.6	0.1	4.2	0.9	Corrêa and Corrêa (1996)
Bactris gasipaes	–	Rondônia/BR	D + W	2.52	–	–	–	–	–	–	Quisen et al. (1996)
Agroforestry system	–	Rondônia/BR	D + W	4.97	–	–	–	–	–	–	Quisen et al. (1996)
Agroforestry system	–	Rondônia/BR	D + W	3.87	–	–	–	–	–	–	Quisen et al. (1996)
AS1-agrosilvicultural	5	Manaus/BR	W + D	3.01	2.28	1.01	0.13	0.94	6.19	2.01	This study
AS2-agrosilvicultural	5	Manaus/BR	W + D	4.11	3.03	1.43	0.21	1.61	8.26	1.92	This study
ASP1-agrosilvopastoral	5	Manaus/BR	W + D	3.38	1.97	1.45	0.14	0.91	8.79	1.72	This study
ASP2-agrosilvopastoral	5	Manaus/BR	W + D	4.07	2.29	1.66	0.12	1.09	7.62	1.79	This study

BR = Brasil; PE = Peru; D = dry season; W = wet season; – data not available.

before the fall of the *Theobroma* leaves. The fact that P was the element with the lowest concentrations in the litter layer of all treatments and dominant plant species, may also reflect some leaching of this element from the accumulated litter layer on the soil (Luizão and Schubart 1987). The P concentrations in leaf litter material found in the treatment AS2 (multi-strata), in the two seasons (Table 4), were higher than in some primary forests in Brazilian Amazonia (Luizão 1995; Villela 1995) and in Sarawak (Proctor et al. 1983) (Table 4).

The K concentrations in the litter layer, even the highest ones, found in the treatment AS2, were smaller than in mature forests in Sarawak and in Maracá (Proctor et al. 1983; Villela 1995); they were also lower than the values presented by Luizão (1995) for a tropical lowland rain forest and by Mckerrow (1992) for a 5-year-old second growth, both in Manaus (Table 4). However, the values in the AFs were greater than those presented by Corrêa and Corrêa (1996) for plantations of *D. ovalifolium* in Manaus. The potassium is the most typical element for mineral leaching from the litter layer on the soil (Luizão and Schubart 1987). The leaching was likely the main reason of lower K concentrations in the litter layer on the soil, especially in the leaves, during the wet season, when this process is accentuated. The K concentrations were always greater in the dry season, despite the lack of significant differences among the treatments and the dominant plant species, in both seasons (Table 3).

The Ca concentrations in the AFs (even the largest ones, found in AS2 and ASP1), were always lower than those found for lowland tropical rain forests in Brazilian Amazon (Luizão 1995; Villela 1995), and for *Dipterocarpus* forest in Sarawak (Proctor et al. 1983) (Table 4). In the present study, the second growth presented lower Ca concentrations than the younger second growths studied by Mckerrow (1992), in the same study area. Costa et al. (1998) found concentrations slightly larger in 11-year-old reforested plots in Pará (9.15 g kg^{-1}) than in the treatments AS2 and ASP. In the same way as for K, the planted trees and the green manures in the inter-rows seem to be important sources of Ca.

The Mg was the macronutrient with more stable concentrations, among all the treatments and dominant plant species. The Mg concentration in

the treatment AS1 was higher than in lowland tropical rain forests of Brazilian Amazon (Luizão 1995; Villela 1995) and in *Dipterocarpus* forest in Sarawak (Proctor et al. 1983); it was also larger than in the reforested site studied by Costa et al. (1998) in Pará. The control presented a similar value to that presented by Mckerrow (1992) for younger second growths in the same study area (Table 4). The Mg concentration under *Desmodium* cover (Table 3) was larger than the values presented by Corrêa and Corrêa (1996) (Table 4). In both seasons, the largest concentrations were found in the litter layer under palm trees, indicating these plants as important sources of Mg for AFs.

In the woody component of the litter layer, the largest concentrations (not shown) of total carbon were found in the AS2 in both seasons ($F = 9.1$ and $F = 7.7$; $p < 0.001$, respectively, in the wet and dry seasons). Greater C concentrations were found under palm trees, *Theobroma* and pioneer species than under the other species, in the wet season ($F = 4.4$; $p < 0.001$) and under *Brachiaria* and *Theobroma*, in the dry season ($F = 7.3$; $p < 0.001$). Woody litter mostly influenced by *Desmodium* and *Brachiaria* had higher N, K and Ca concentrations; *Theobroma*-dominated litter showed higher concentrations of P, K and Mg; inter-rows litter had higher P; the palm litter, higher Mg; lowest concentrations generally were found in the litter dominated by the pioneer species.

Carbon and nutrient stocks in the litter layer

The largest stocks of carbon in the litter layer (wet and dry seasons) were found in the secondary vegetation (control plots); among the AFs, in the dry season, the treatment AS2 presented the largest C stocks (Table 5). Among the analyzed macro-nutrients, nitrogen (N) presented the largest stocks in the litter layer (15.7–82.6 kg ha^{-1}), in all the studied treatments. The stocks of N in the leaves and in the woody material were always greater in the control and ASP2 (Agrosilvopastoral System 2), in both seasons (Table 5). These results largely reflected the higher plant biomass in the control and the higher N concentrations in the ASPs. In general, litter of the ASPs presented higher concentrations of N, mainly because of *Desmodium* cover and the *Inga edulis* trees planted in these systems. In the present study, the leaves and the woody material of the litter layer under *Desmodium* and *Brachiaria* presented concentrations of N relatively high, with 1.6% (*Desmodium*) and 1.3% (*Brachiaria*) in the leaves, and 1.35% (*Desmodium*) and 1.3% (*Brachiaria*) in the shafts and woody material. These values were higher than those found in Manaus by Corrêa and Corrêa (1996) for the litter layer of *Desmodium*, but much lower than in Peru (Yurimaguas), where the leaves of *Desmodium* had 2.37% of N (Palm and Sanchez 1991). The surprisingly high N concentrations in the litter layer under pasture in the present study was due to the mixture of grass with *Desmodium*, which clearly dominated the litter layer production and soil cover. The difference among the concentrations of N of the fresh leaves of the palm trees (2.7%) (Uguen 2000) and its litter layer (1.05%, in this study), suggest that the retranslocation of N before the litter fall is an alternative strategy of N conservation for the palm trees (*E. oleracea* and, mainly, peach palm).

P was the element with the smallest stocks in the litter layer (Table 5), varying from 0.20 to 1.01 kg ha^{-1} and the values were always a little higher in the wet season than in the dry season. The stocks of K (from 1.15 up to 11.8 kg ha^{-1}) were larger in the treatment AS2 and in the control plot (CAP) than in the other treatments, in both seasons (Table 5).

Ca showed the second largest stock in the litter layer (Table 5), and the largest values were found in the dry season. The stocks varied from 6.45 to 57.6 kg ha^{-1}; and were higher in the control and in the ASP2 in the wet season, and in the AS2 and in the control in the dry season. The stocks of Mg in the litter layer (Table 5) varied from 2.14 to 12.6 kg ha^{-1}, always with the highest values in the dry season. The stocks of Mg were larger in the control and ASP2 in the wet season, and in the AS2 and in the control in the dry season.

The higher stocks of P (as well as eventually K and Ca) in the ASP2, which received larger input of green manures, may be explained by the larger concentrations of P in the litter layer at the inter-rows. These larger concentrations were likely result of the free P input through rainfall, as well as of the masses of leaves of *Inga* and *Gliricidia* (pruned regularly and used as green manures) which are added to the soil, together with the remains of regular weed cuts. Green manures were

Table 5. Stocks of carbon and nutrients in the litter layer in the agroforestry systems and in the secondary vegetation control, in the wet and dry seasons, in central Amazonia, Brazil.

Treatments	C	N	P	K	Ca	Mg
Wet Season (kg ha^{-1})						
AS1	727a	15.7a	0.20a	1.15a	6.45a	2.14a
AS2	1236a	38.1a	0.54b	3.14b	13.7a	3.69a
ASP1	1335a	38.0a	0.38b	1.99a	21.7b	3.13a
ASP2	1647a	47.7b	0.33a	2.62b	22.5b	4.69b
CAP	2457b	50.9b	0.43b	3.10b	26.1b	5.85b
Dry Season (kg ha^{-1})						
AS1	2168a	45.1a	0.57a	5.75a	35.5a	10.6a
AS2	3345b	73.1b	1.01b	9.92b	57.6b	12.6b
ASP1	1888a	52.9a	0.42a	4.56a	41.7a	7.75a
ASP2	2407a	75.1b	0.49a	6.93a	36.0a	9.28a
CAP	3966b	82.6b	0.68b	11.8b	50.2b	11.8b

The values represent the mean of three blocks ($n = 3$). Values with different letters in the columns indicate significant differences of nutrient stocks between treatments ($p < 0.001$), within each season. Treatments as in Table 1.

generally applied to soil surface three times a year. During the year following the present study, the AS1 received 5160 kg ha^{-1} of *Gliricidia* (representing 16.8 kg N, 0.94 kg P, 6.23 kg K, 2.87 kg Ca, and 2.11 kg Mg (Gallardo-Ordinola 1999). The AS2 received 598 kg of *Gliricidia*, plus 2050 kg of *Inga* (total = 8630 kg), representing 24.5 kg N, 1.43 kg P, 857 kg K, 5.31 kg Ca and 2.95 kg Mg.

Addition of these organic residues play an important role in the biomass production and nutrient accumulation of the AFs (Palm and Sanchez 1991). They stimulate the soil microbial biomass which represents the most active component of the organic matter and of the nutrient recycling in the soil-plant system (Luizão and Luizão 1991). Therefore, the biomass production of the weeds, with significant stock of nutrients, cannot be wasted, and, after each cut the weed biomass should be redistributed between the rows of cultivated plants as a soil cover and a source of nutrients (E. Wandelli personal communication, 2003).

Conclusions

Although all the 5-year-old agroforestry systems (AFs) had lower litter-layer amounts than the second growth, likely reflecting a lower litter production, the litter layer of the AFs showed a better nutritional quality (as represented by their C:nutrient ratios). This may imply in a faster decomposition and nutrient recycling process in the AFs.

In general, the leaves (and other faster-decomposing materials) appeared as the main sources of C and nutrients in the litter layer of the AFs. The woody material of the litter layer appeared as important source of Ca and Mg just in the dry season, when Mg concentrations were high and the amounts of woody material in litter increased.

In the AFs, *Desmodium* and the planted trees (including the legume species *Inga edulis* and *Schylozobium amazonicum*) appeared as important sources of N to soil; the incorporated weeds and the green manures (*Gliricidia* and *Inga*) were important sources of P; the planted timber trees and the green manures were important sources of K and Ca, while the palm trees seemed to be the main source of Mg in the system AS1.

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